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Ad Hoc Networking for Unmanned Ground Vehicles: Design and Evaluation at Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance On-The-Move

by Barry J. O'Brien, David G. Baran, and Brian B. Luu

ARL-TR-3991   **November 2006**

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14. ABSTRACT

The U.S. Army Research Laboratory (ARL) participated in the command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) On-the-Move (OTM) experiment that was held at Fort Dix, New Jersey, during the summer of 2006. The C4ISR OTM experiment was designed to examine the effectiveness that advanced C4ISR technologies have on an Army Future Combat Systems (FCS)-based Infantry Company and Reconnaissance Troop. The experiment included live Soldier exercises, with each Soldier being connected to a battlefield tactical network. ARL's objective in the exercise was to demonstrate system-level integration of developing technologies for small unit combat operations aimed at improving situational awareness. ARL brought to the experiment expertise in unattended ground sensing technology, wireless mobile ad hoc communication, and information fusion. The ARL C4ISR system included multimodal unattended ground sensors, a trip wire imager, multiple human-portable robotic vehicles (PackBots), and an unmanned scout/light cargo carrying robotic vehicle (R-Gator).

This report discusses the work done at ARL on the mobile ad hoc networking system for controlling robotic assets, which was created for the C4ISR OTM experiment. Further, it examines the results of a number of field tests performed in preparation for and during the experiment.

15. SUBJECT TERMS

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Contents

List of Figures

List of Tables

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1. Introduction

The U.S. Army Research Laboratory (ARL) participated in the command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) On-the-Move (OTM) experiment that was held at Fort Dix, New Jersey, during the summer of 2006. The experiment was hosted by the Communications and Electronics Research Development Engineering Center (CERDEC) Special Projects Office (SPO) C4ISR Integration Test bed, Fort Monmouth, New Jersey.

The C4ISR OTM experiment was designed to examine the effect that advanced C4ISR technologies have on situational awareness (SA) of an Army Future Combat Systems (FCS)-based infantry company and reconnaissance troop. The experiment included live Soldier exercises, with each Soldier being connected to a battlefield tactical network. Also connected to the tactical network was a suite of manned and unmanned sensor assets controlled via a cohesive command and control environment[1].

ARL's objective in the exercise was to demonstrate system-level integration of developing technologies for small unit combat operations aimed at improving SA. ARL brought expertise in unattended ground sensing technology, wireless mobile ad hoc communication, and information fusion to the experiment. The ARL C4ISR system included multimodal unattended ground sensors, trip wire imagers, multiple human-portable robotic vehicles (PackBots), and an unmanned scout/light cargo carrying robotic vehicle (R-Gator). These disparate technologies were integrated into an overall C4ISR system with the use of a combination of proprietary and commercial off-the-shelf (COTS) components, and they communicated wirelessly via various methods. Users can control the system in a number of ways, including using a remote mobile platform mounted in a tactical high mobility multipurpose wheeled vehicle (HMMWV) or via an operator control unit (OCU) carried by a dismounted Soldier. In addition, the ARL C4ISR system was integrated into the Force XXI Battle Command, Brigade and Below (FBCB2) display suite, which provided users with the capability of controlling and accessing data from multiple systems at a central location.

2. ARL Involvement

Four of the six technology directorates at ARL participated in the C4ISR OTM experiment. The Weapons and Materials Research Directorate (WMRD) provided a number of unmanned aerial vehicle (UAV) technologies, the Human Research and Engineering Directorate (HRED)

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[1]C4ISR OTM Program Overview, www.c4isrotm.net (cached page only).

provided operational and usability assessments, the Sensors and Electron Devices Directorate (SEDD) provided multimodal unattended ground sensors (UGS), and the Computational and Information Sciences Directorate (CISD) provided unmanned ground vehicle (UGV) technologies and integration software. This report focuses on the work that CISD performed for the experiment.

HRED played a significant role in gathering useful feedback from the Soldier end users of the unmanned systems brought by CISD and SEDD. By administering surveys to the dismounted Soldiers during the exercises, HRED personnel were able to gain insight into whether the new technologies improved Soldiers' perceived SA, to gain immediate feedback about how the Soldiers were using ARL technologies, and to document any issues that arose during their use in the field.

CISD and SEDD collaborated on integration efforts in preparation for the experiment. SEDD contributed a suite of UGSs to the experiment and wanted to integrate into CISD's command and control software so that sensor data could be displayed on a mapping system. Working closely with CERDEC, the two directorates integrated communications from the sensors to platoon-level vehicles using CISD's Blue Radio, a low power and low data rate radio designed for sensor networking. Further, data provided by the UGSs was integrated into two pieces of CISD software, Sensed Object Server (SOS) and Tactical Object Server (TOS). These applications ran on a server in the platoon-level vehicle. SOS converted low-level data from sensors into a more usable format, which TOS then converted into tactical symbols that could be displayed on FBCB2, the mapping system used at C4ISR OTM, via a CERDEC message translator called the Conduit Gateway. These integration efforts allowed sensor data to appear as speed, position, and track (SPOT) reports in the same manner as user-generated reports from the unmanned assets. Because of the high level of collaboration among CISD, SEDD, and CERDEC, this system was able to be brought on line in the field in less than one day.

The other pieces of technology that CISD brought to the experiment were its unmanned systems and corresponding mobile ad hoc network (MANET). CISD brought two robotic platforms to the experiment. The first was the PackBot[2] Explorer, manufactured by iRobot, which acted as the FCS small unmanned ground vehicle (SUGV) surrogate. The second platform was the R-Gator[3], also manufactured by iRobot, which acted as the FCS armed robotic vehicle platform in its reconnaissance, surveillance, and target acquisition (ARV-RSTA) configuration. CISD removed all iRobot proprietary application software from both platforms, choosing instead to write its own robotic control and network architecture software, giving it a more robust feature set while maintaining its openness and extensibility. Connecting each robot to its OCU as well as to other robots was a MANET built from COTS components that had been altered by CISD to operate a modified version of open-source MANET software. The MANET features allowed the

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[2]PackBot is a registered trademark of iRobot, Inc.

[3]R-Gator is a trademark of iRobot, Inc.

network operational range to be extended by the emplacement of CISD designed ad hoc drop-off nodes along a chosen path, thus giving the network traffic the ability to "hop" from one node to the next, even on non-line-of-sight (NLOS) paths.

This report focuses on the design, implementation, and results of the MANET that was implemented for robotic control in the C4ISR OTM experiment. We discuss the research relating to MANET design and the low-cost COTS equipment used to implement the design. Further, discussion focuses on the drop-off nodes, highlighting their low cost and ability to extend the MANET. Finally, we discuss the results of numerous field experiments and evaluations performed in preparation for and during the C4ISR OTM experiment.

3.   Mobile Ad Hoc Networks

A MANET is generally defined as a wireless, self-configuring ad hoc network that consists of mobile nodes connected together by wireless links. These mobile nodes can act as routers to forward routing information and data to each other, maintaining network connectivity among them. By exchanging routing information between nodes, these routers can freely move and organize themselves into a self-configuring network of random shapes or topologies.

Because of its versatility, a MANET is a very useful tool for meeting Army battlefield communication requirements. The mobility provided by a MANET is not only a key factor for survivability on the battlefield but also provides convenience and flexibility in executing the Army mission. The ad hoc capabilities allow the Army to deploy and use network communications without a fixed infrastructure. The MANET can be quickly deployed in urban environments or on battlefields where network infrastructure can be destroyed, unreliable, or unavailable. The self-configuration capability of a MANET allows mobile Army units be very adaptive to topological changes without manual reconfiguration of the network.

ARL has researched MANETs and their application for military uses. Several self-configuration protocols are used for implementing a MANET, but there are two main MANET protocol groups: proactive and reactive. In reactive MANET protocols (RMPs), routing information between nodes is determined when communications are needed. Thus, communication overhead is less but network communication latency is high. Conversely, in proactive MANET protocols (PMPs), routing information of nodes is constantly exchanged on the network, yielding high network overhead but low network latency. An open source version of a proactive MANET protocol is called Optimized Link State Routing Daemon (OLSRD)[4]. OLSRD is an implementation of the Optimized Link State Routing (OLSR) protocol.

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[4]Developed by Andreas Tønnesen and Thomas Lopatic (www.olsr.org).

Typically, MANET nodes have the capability to communicate with each other but do not have any specialized processing capabilities to perform dedicated tasks such as computation, video or file serving. Dedicated computer nodes for specific tasks must be equipped with both a wireless local area network (LAN) interface and the MANET protocol in order to communicate in the MANET environment. These requirements will make dedicated computer nodes less mobile since they will be larger and heavier and will consume more power. "MANETized" computer nodes are not readily available as already defined COTS products since there is limited demand for MANET capabilities outside military applications, and no actual MANET protocol standards have been established. The solution is to develop and implement gateway capabilities from regular computer networks such as Ethernet to MANET and vice versa. With this implementation, the MANET nodes communicate with one another while the dedicated computer nodes are connected to the MANET nodes through a regular network interface. This technique is called the sub-network gateway to MANET technique.

For implementation of a MANET, ARL has employed the ad hoc capability of wireless LANs such as Institute of Electrical and Electronics Engineering (IEEE) 802.11a/b/g as a means to achieve mobility. The IEEE 802.11g wireless standard is the best choice since it provides faster data rates (54 Mbps maximum) and farther wireless operational distance than the IEEE 802.11a or IEEE 802.11b protocols.

In 2004, for the Department of Defense (DoD) Horizontal Fusion program, ARL developed MANET nodes called black ad hoc nodes with the support of BBN Technologies and Telecordia, Inc. The MANET protocol used for the black ad hoc node was Hazy Sighted Link State (HSLS), which was developed and licensed by BBN Technologies. Since the black ad hoc nodes were designed specifically for the Horizontal Fusion program and were the first experimental MANET, they were limited in capability and performance.

In 2006, with the maturity and proliferation of wireless LANs, ARL developed new MANET nodes, called blue ad hoc nodes, which have a smaller form factor and better performance. As a cost-saving measure, the blue ad hoc nodes were built with Linksys wireless LAN routers and the open source OLSRD. The Linksys router is built with an internal 100-mW amplifier for 802.11g wireless LAN protocol which allows for long distance wireless operation (as far as 500 m) without the use of high-gain antennae. It is also equipped with two wired Ethernet 10/100 interfaces to allow implementation of the sub-network gateway to MANET technique for connecting dedicated computer nodes. With the sub-network gateway technique, the sub-network (subnet) attached to a MANET node is advertised in the MANET environment so that the gateway to this subnet is through its MANET node. Figure 1 depicts a MANET topology with subnets attached to some MANET nodes.
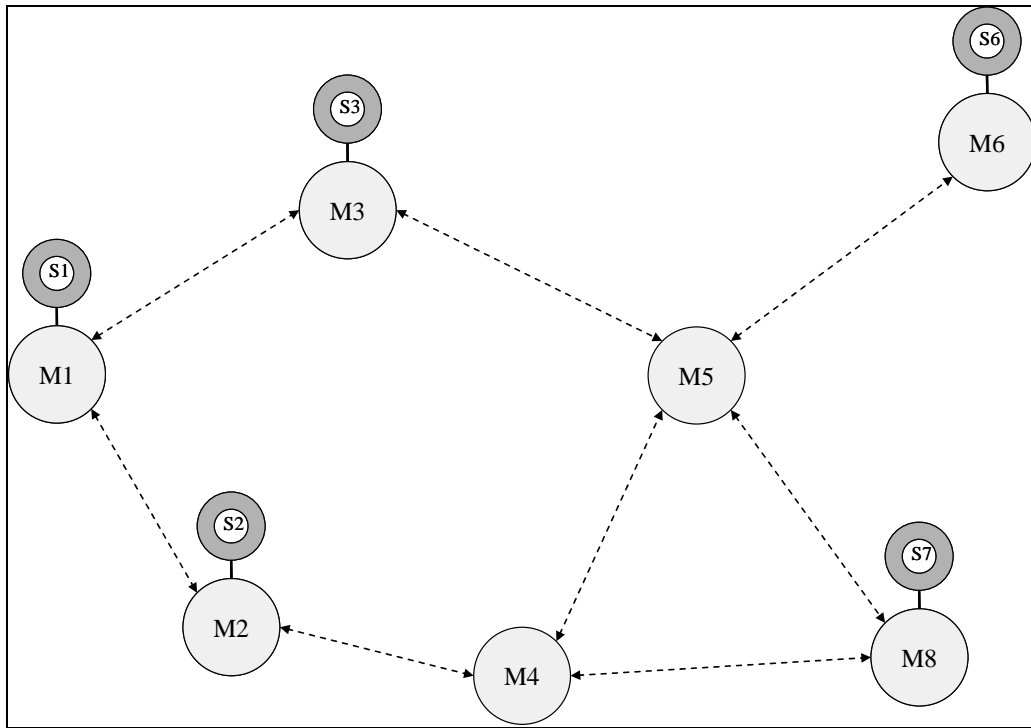
Figure 1. Representation of a MANET topology with subnets attached to some MANET nodes.

Examples of subnets used by ARL are robotic platforms, robotic OCUs, and mobile video servers. By connecting to a MANET node, the robotic OCU can maneuver a remote robot connected to another MANET node. Similarly, mobile video servers attached to a MANET node can provide streaming video to any non-MANET nodes on subnets that are connected to MANET nodes.

Intermediate MANET nodes forward network information and data of other MANET nodes. Thus, MANET nodes can be used to extend the operative range of linked nodes by hopping between MANET nodes. These intermediate nodes do not have to be connected to any subnets and are called drop-off nodes.

To minimize cost and developed time, the Battlefield Communication Network Branch (CI-CN) of ARL's CISD developed ad hoc nodes using Linksys wireless LAN routers (models WRT54GS and WRTSL54GS) and open source software (OpenWRT[5], OLSRD and OpenVPN[6]). The network facility of the Linksys WRTSL54GS consists of two wired 10/100 Ethernet interfaces and one wireless LAN interface (capable of IEEE 802.11b/g). OpenWRT is a version of the Linux operating system with a small footprint specifically designed for embedded devices. Two other important software components used in the ad hoc nodes for the C4ISR OTM experiment were OLSRD, an open-source proactive MANET routing software, and OpenVPN, an open-source virtual private network (VPN) software used for security and encryption.

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[5]OpenWRT was developed by Mike Baker (openwrt.org).

[6]OpenVPN is a trademark of OpenVPN Solutions LLC.

Secure communications in the MANET are achieved with encryption provided by Wired Equivalent Privacy (WEP) and OpenVPN. The WEP protocol, which is part of the IEEE 802.11 wireless networking standard, encrypts network frames before transmitting to the air medium. The WEP encryption provides confidential communication at the physical and data link layer, known as layers 1 and 2, respectively, in the Open System Interconnection (OSI) model of communication network. For strong encryption, a 128-bit-key encryption is used for the WEP of blue ad hoc nodes. Although there are security limitations of WEP when one is using short encryption keys (40 or 64 bits), WEP encryption is good enough to provide protection for MANET routing information, which is usually not as protected as internet routing information.

The main function of OpenVPN is to provide secure communication of private networks over unsecured public networks such as the internet. To achieve secure communication, OpenVPN creates cryptographic tunnels through public networks to link private networks together. For application in a MANET, OpenVPN is used to create VPN tunnels to securely link subnets, which are attached to MANET nodes. OpenVPN provides communication encryption at the network layer (layer 3 of the OSI model), establishing an end-to-end communication encryption between two MANET nodes. With cryptographic tunneling protocols, OpenVPN enables confidentiality (privacy), authentication (sender and receiver identity), and integrity (unaltered data) for communications in a MANET. Figure 2 illustrates a VPN tunnel connecting subnets s1 to subnet s6.
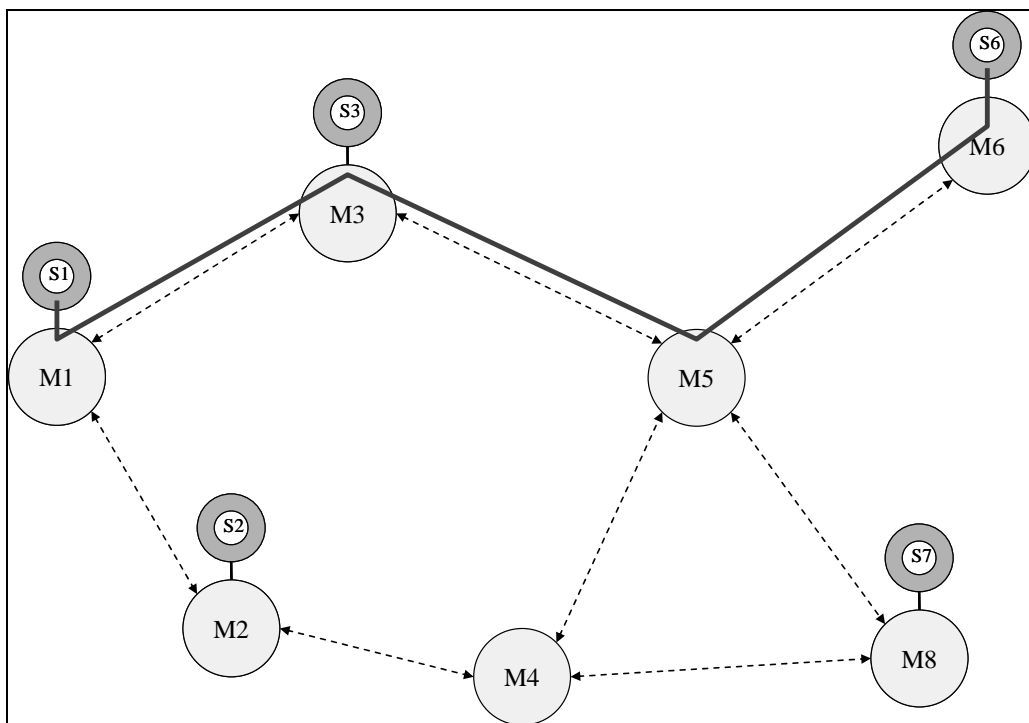

Figure 2. A VPN tunnel connecting subnets s1 and s6.

4. Design and Implementation

4.1 Linksys Router Software Installation and Configuration

Before ad hoc communication payloads were designed to provide network connectivity to all the system assets in the MANET, configuration of the COTS wireless routers had to be performed. For each of the nodes, configuration began with a new, unmodified Linksys wireless LAN router.

The first step of the configuration process was to replace the proprietary firmware with open-source software that contained all the software components needed for the MANET, namely, OpenWRT, OLSRD, and OpenVPN. This .bin file was flashed onto the router via the web-browser-based interface and was rebooted.

Following the firmware installation, a telnet connection to the router via the default internet protocol (IP) address[7] was established. A manual reboot was then performed to allow OpenWRT to complete initialization of the new Linux file system.

The telnet connection was then re-established, and a password was set on the router to prevent unauthorized access. A set-up script file and tar files needed by the script were securely copied to the /tmp directory. The set-up tar file was extracted into the /tmp folder, and then the set-up script was executed. The node host name and IP address were set as desired when prompted by the script, with a 192.168.x.1 format. The settings were saved to memory with the nvram command, and the router was rebooted to finish IP configuration.

The last step was to configure the VPN. We accomplished this by running a vpn configuration script, which prompted for the two IP addresses in the VPN pair, for example, 192.168.125.1 and 192.168.135.1. These two addresses would correspond to a robot-OCU pair. The script then produced a configuration file for the VPN, which was virtually linked in the OS to point at the vpn.conf file. After a final reboot, router configuration was completed.

4.2 PackBot Payload Design

In order to test the functionality of the MANET, several different platforms required ad hoc nodes to be developed, including two robotic platforms. The first robotic platform discussed is the iRobot PackBot Explorer.

The PackBot Explorer standard communications protocol is the IEEE 802.11g wireless standard. The platform is designed with a payload bay so that modular payloads can be easily integrated onto the robot. The payload interfaces to the robot through a proprietary 45-pin connector. This connector allows the payload to communicate with the robot computer through a variety of

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[7]The default IP address of the WRTSL54GS is 192.168.1.1

interfaces, including universal serial bus (USB) and Ethernet, and to draw 24-V DC power from the robot.

In order to provide a weather-resistant payload, the COTS-based system had to be packaged. Because of time constraints, PackBot payload containers made from rapid prototyping plastic were used. Although the container was weatherized, the lightweight plastic was not ideal for a ruggedized system. However, since the payload bay sits within the frame of the robot, the payload receives a fair amount of protection from the robotic platform itself.

Figure 3. PackBots showing ARL ad hoc payloads.

In this design, the reconfigured Linksys router was removed from its plastic case and the antenna was removed. This was done so that the router could be repackaged into the payload sized container. Standoffs were used to mount the router board to the bottom of the payload container, to prevent the electronics from being jostled while the robot was in motion, and to position it above the bottom of the payload if moisture entered the container.

The Linksys router required 12-V DC power, but the power provided by the robot is 24-V DC; therefore, the payload required the addition of a 24-12-V DC-DC converter. A PC-104 style DC-DC voltage converter was selected to accomplish this because of its small form factor. The voltage converter was mounted into the payload container below the footprint of the router board.

An antenna mount was then placed on the outside of the payload package to replace the standard router antenna, which had been removed to facilitate packaging. To minimize the loss of gain, the new antenna cable was soldered directly to the router board on one end and connected to the antenna via a single radio frequency (RF) connector on the other end. This design eliminated the need for multiple gain-reducing RF connectors between the board and the antenna. A high gain, flexible antenna originally in use on the PackBot was selected for the payload. This was to accommodate the operational capabilities of the PackBot, which include the ability to drive while inverted.

Once all the payload components were designed and constructed, the payload hardware was integrated with the robot. A small integrated circuit board that provided 24-V DC power and Ethernet interfaces with the proprietary connector was added to the payload. Power was routed to the voltage converter and then connected to the router with a custom connector plugged into the existing DC power receptacle. Signal was sent directly between the Ethernet port on the breakout board and the Ethernet interface on the router via a standard Cat.5 cable. The final step was to re-configure the software and IP address of the PackBot so that it used the new ad hoc payload as its gateway.

4.3   Gator Payload Design

The second robotic platform that was modified was an iRobot/John Deere R-Gator. The R-Gator is a larger platform developed for transport and RSTA purposes. It is capable of being driven manually, tele-operated, or with semi-autonomous techniques such as waypoint following. The platform is multi-functional and can be used to transport people, supplies, or smaller robotic assets such as the PackBot Explorer.

The R-Gator is designed with a large payload container that separates the passenger seats and cargo area in the rear of the robot. This container is used to house the electronics necessary to control the platform as a robotic asset. Since there was available space in this container, the COTS ad hoc node did not need to be housed in a separate weather-resistant and ruggedized housing. Instead, the router could be placed in the available free space.

The R-Gator is equipped with two antennas, so a slightly different Linksys router (Model WRT54GS) was used. The selected router had two antenna input, making it capable of taking advantage of antenna diversity. Antenna diversity uses multiple antennas to use multi-path environments, thus improving performance and providing greater signal range.

The robot had two available power points in the payload, one operating at 36-V DC unregulated and the second operating at 24-V DC regulated. However, like the previously integrated version of the Linksys router, this version also required an input of 12-V DC. To provide this, the 24-V DC power point was used, and a simple 24-12-V DC-DC converter was installed. Since the regulated 24-V line was not completely immune to slight variations in voltage level as other components in the robot were switched off and on, and the tolerance to power variations of the

router board was unknown, the necessary resistors and capacitors were soldered onto the power converter to ensure a stable 12-V DC output.

Once the ad hoc node was powered, the signal needed to be connected to the computer systems. Unlike the PackBot, which has a single central processing unit, the R-Gator contains two computer systems. One handles robotic control, while the other handles image processing and geo-location via a compass and GPS unit. Each was connected into the router via an Ethernet connection and was given a unique IP address in the appropriate IP range in order for the router to serve as the gateway for both machines.

4.4   Drop-off Node Design

Preliminary testing indicated that the communications range of an ad hoc node was approximately 0.2 mile. In order to extend the range of the communications network to a suitable distance for field operations, as well as to allow assets to be controlled in NLOS situations, drop-off ad hoc nodes were added to the system. These nodes were needed to act as repeaters that could pass communications between multiple robot-OCU pairs. They needed to be capable of running for long periods of time without an external power source and be easily transportable so that they could quickly be emplaced and rearranged in the field as the conditions of the battlefield environment dictated.

To solve the power problem, a 12-V DC battery pack, which is intended for use in portable DVD player applications, was chosen as a power source. The battery was lightweight and had a small form factor. Testing of the battery pack determined that it could provide power to an ad hoc node for as many as 12 hours, well beyond the power requirements of the drop-off node.

To provide a fieldable drop-off node solution, the system had to be weather resistant and easily transportable. We accomplished this by packaging the node components in a small (10 x 8 x 5 inches) Pelican case. The router board was secured to the bottom of the Pelican case with standoffs to prevent it from being damaged during transport. The battery was secured to the bottom of the case with industrial strength Velcro[8] so that it could be held in place but could also be easily removed and replaced as needed. An AC adaptor was needed to charge the battery when the system was not fielded, and it was desired that the antenna be removable to limit potential damage during transport. Thus, the cases were designed to allow for enough space to store the AC adaptor and antenna so that a single drop-off node unit was completely self-sustaining.

The stock Linksys router antenna was removed from the router unit so that it could be mounted inside the Pelican case. This was done to create a weather-resistant system and so that a 7-dB gain antenna could be added to the system. The higher gain antenna was chosen to increase the effective range of an individual node. In order to limit the loss between the antenna and the

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[8]Velcro is a registered trademark of Velcro USA, Inc.

board, care was taken to limit the number of connectors used, while the length of the antenna wire was kept to a minimum. Simultaneously, the design requirements necessitated that the wire be long enough to help the lid of the case to open easily so the system could be assembled and disassembled. A hole was drilled through the plastic router case lid so that no strain would be placed on the solder joint if the wire were pulled when the case was opened or closed. The RF connector selected was a reverse polarity TNC female connector, which mated with the chosen antenna. The need for this non-standard connector required that the wiring assembly be fabricated in house, instead of being purchased from a commercial site.

Figure 4. Internals of ARL ad hoc drop-off node.

Since the design of the drop-off module required the system to be easily transportable, it had an inherently small form factor. This was problematic since the closer the antenna is to the ground, the smaller the range of the node. During field testing, it was determined that the nodes could be strategically placed in trees, just above eye level. This placement was optimal for several reasons. The elevation gain allowed the nodes to operate above the dense scrub oak canopy in the test environment but below the tree canopy, giving us greater range and improved performance. Further, because the nodes were placed slightly above eye level, they were also more difficult to detect by the opposition force as they passed through the theater of operations.

4.5 OCU Node Design

In order to control the robotic assets described, an OCU had to be designed and developed. The OCU had to be lightweight, easy to carry, and ruggedized to protect it from the abuses of dismounted field operations. To accomplish this, a ruggedized tablet PC was selected to provide processing capabilities. The tablet was mounted onto a custom designed metal frame that housed two joysticks for robotic control. The joysticks were connected to the tablet through the USB port. A neck strap was connected to the frame to make the unit easier to carry. The router was mounted to the back of the frame so that everything was connected as a stand-alone system.

The OCU needed to be able to talk on two different networks in order to accomplish its two primary functions:

- Command and control of a designated robotic asset;

- Communication "uplink" to higher echelons in order to forward SA media (video and images) being collected by the robotic platform.

This need for simultaneous communications on two networks required the system to have two network interface cards (NICs). The tablet PC selected in the design phase for this project only had one on-board NIC, so a second was added to the system with the use of a PCMCIA[9] card. The internal routing table on the tablet PC was configured to ensure that traffic destined for the robotic platform always passed through the PCMCIA card, which was connected to the ad hoc router. All other network traffic was routed through the native NIC, which was connected to a Soldier Radio Waveform (SRW) radio that passed data to platoon-level vehicles for dissemination to ground forces. This allowed both devices to communicate with their respective networks without interfering with one another.

Since the router was mounted onto the frame of the OCU, power could be provided from the battery source providing power to the tablet. The tablet required an input of 20-V DC, while the router only needed 12-V DC, but a battery cable was designed to provide both of the necessary voltages to the devices. After testing, it was determined that the cable design was correctly providing the required voltages, but the requirements were causing the battery to be drained unevenly. Therefore, an independent battery for the router was added to the system, increasing router run time but increasing the weight of the system 3.15 lb to 14.05 lb.

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[9]PCMCIA is personal computer memory card international association (now called PC cards).

Figure 5. ARL OCU showing ad hoc node.

5. Test and Analysis

Seven evaluations of the mobile ad hoc system were performed over a 4-month period from May until August in the summer of 2006. The purpose of the evaluations was to obtain some absolute performance metrics (maximum range, allowable video rate) as well as more qualitative metrics relating to the system's ability in various environments and suitability for certain types of operations.

Although the final experiment took place at Fort Dix, not all the evaluations were performed on site. Equipment was shipped to Fort Dix incrementally throughout the summer as it became ready for use. Consequently, engineers only spent a week or two at a time on site with the equipment, which mandated further testing and development at Adelphi Laboratory Center (ALC). Thus, improvements were often made in equipment before shipping as a result of the evaluations at Fort Dix.

For the C4ISR OTM experiment, the MANET was designed to provide a robust and extendable ad hoc network. Its primary application was to provide for tele-operation of the CISD robotic assets. This mode of operation allows the user to remotely control the robotic platform using

only streaming video displayed on the OCU. It had been previously determined that the minimum frame rate required to support tele-operation was approximately seven frames per second[10]. Thus, one of the quantitative measurements was the video frame rate that the network could support in various conditions. The streaming video from the cameras on the robotic platforms was compressed before transmission with the Motion-JPEG compression scheme. The CISD-designed underlying network architecture, known as CIPNet[11], breaks the stream into packets to be sent over the wireless network. On the OCU side, the video stream is displayed by CISD's command and control application, CollectControl. This Windows[12]-based application allows the user to select which asset s/he would like to view and/or control and to control the resolution of the video source and its frame rate.

Figure 6. ARL OCU showing operation of CollectControl.

For the exercise, a VPN was established between each robot and OCU pair. This was requested by the C4ISR OTM architects and limited the actual ad hoc operation of the network. However, this VPN did not affect the ability of network traffic to hop between end nodes via the drop-off nodes. It was designed so that all robot-OCU pairs could use any given drop-off nodes as

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[10]French et al., "Modes of Control of an Unmanned Ground Vehicle (UGV)", presented at the ARL Collaborative Technology Alliance (CTA) Symposium as part of the Advanced Decision Architectures (ADA) CTA, 2003.

[11]Choy, S. "CIP Network Agent Service API User's Guide" ARL, Adelphi, MD, February 2001.

[12]Windows is a trademark of Microsoft Corporation.

hopping points, since the drop-off nodes were not subject to the VPN limitations. Instead, they just passed all traffic and let the end nodes do the VPN administration.

5.1 Initial Robotic Field Test (Fort Dix, New Jersey)

Because of the short developmental schedule, no rigorous testing had been accomplished by CISD before the delivery of the robotic systems on site at Fort Dix. They were confirmed to be operational, but no range, performance, or other tests were performed before five systems were shipped.

System evaluation was performed on Range 47 at Fort Dix. The test was performed on 4 May 2006 under sunny skies. The test site was a large, mostly flat, rectangular field with a few rolling hills and a dirt road bisecting its area down the middle. There were no trees in the range, but the range was covered by areas of scrub brush and sand. Also present were a number of training dummies and vehicles, since the site also served as night vision training for Soldiers stationed at Fort Dix.

Figure 7. Initial robotic field test site at Fort Dix, New Jersey.

5.1.1 Objectives

The objectives of this test were straightforward. First, we wanted to determine how far our new ad hoc communications network between the OCU and robot could acceptably operate a robotic asset. Secondly, we hoped to determine the additional communications range that an ad hoc

15

drop-off node emplaced between the OCU and robot would provide, as well as how the network performed when multiple drop-off nodes were emplaced. Finally, we wanted to determine the effect the VPN had on operational range and video performance.

5.1.2 Results

The distances listed in table 1 reflect the point at which driving the vehicle via the OCU video became impossible because of increasingly erratic control capabilities and laggy or bursty video. In most cases, the ad hoc network maintained connection, but data transmission delays prevented timely control. When used, the drop-off nodes were positioned on the ground on a berm approximately 0.3 m above the road level or on cinder blocks set on the berm, approximately 0.75 m above the road level.

Table 1. Results of initial robotic field test.

Distance Test Performed	Number of Drop-Off Nodes	Height of Drop-Off Nodes	Location of Drop-Off Nodes	VPN	Result
OCU to PackBot	0	N/A	N/A	Yes	193 m
OCU to PackBot	1	0.3 m	160 m	Yes	321 m
OCU to PackBot	1	0.75 m	160 m	Yes	418 m
OCU to PackBot	1	0.75 m	160 m	No	434 m
OCU to PackBot	2	0.75 m, 0.3 m	160 m, 354 m	Yes	434 m
OCU to R-Gator	0	N/A	N/A	Yes	418 m
OCU to R-Gator	1	0.3 m	321 m	Yes	692 m

5.1.3 Discussion

Generally, the ad hoc communications system worked better than was anticipated and much better than the previous generation "black box" ad hoc nodes. Not only were they packaged in a significantly smaller form factor, but the software appeared more robust, working every time it was powered on.

The first noteworthy result of these tests was the distance at which we were able to control the robots. The old "black box" version of ad hoc nodes allowed operation of a robotic platform at distances rarely greater than 100 m. With the new system, we were consistently obtaining 2 to 4 times greater distance from the OCU to a robot—a significant improvement. In all cases, the video was viewed in CollectControl at a rate greater than 10 frames per second until the robots became un-drivable, at which point, the frame rate dropped significantly.

The most difficult problem we had was with the video becoming bursty at lower frame rates (less than 10 frames/second) as the robot to OCU distance increased. The operator observed the video smoothly streaming, when a slight pause where the video seemed to stop, followed by a large number of old video frames being displayed rapidly. Many times, the robot was correctly executing the commands sent by the operator, but the video displayed on the OCU did not

correctly reflect the robot executing the commands. On some occasions, both the control commands on the robot side and the video on the OCU side seemed to queue up and then burst out. The effect was the robot briefly driving itself after the operator had stopped moving the joystick. This is an important safety issue that needs to be studied further. Preliminary discussions led us to suspect the VPN as the culprit. However, when the VPN was removed, we observed the same behavior. Additional research needs to be performed in order to isolate the cause of this problem.

CollectControl had two further issues. The first is the issue of a platform "commandeering" driving control from the operator. This is a known issue where CollectControl de-selecting the "driving" button while an operator is controlling a robot at seemingly random intervals, causing the robot to stop moving. This is obviously an issue that needs to be resolved, since losing control of a robot when no other issues are at play (i.e., communications problems) is unacceptable. The second issue is that CollectControl de-selects the "driving" button when the ad hoc network experiences a slight drop-out. This is technically the correct functionality. However, the ad hoc network infrequently experiences drop-outs that occur momentarily for no apparent reason, and it regains a strong connection immediately afterward. Further investigation is needed to find a solution that prevents CollectControl from losing control during short interruptions in network connectivity.

As mentioned before, the VPN software on the ad hoc nodes was originally targeted as a possible cause of the bursty video performance. While the removal of the VPN software was found not to be the cause of the problematic video performance, it did have an effect on the network. Removing the VPN software reduced reconnect time, following one of the nodes being powered off, from approximately 3 to 4 minutes to approximately 30 seconds. The engineers in CI-CN will be investigating a permanent solution to reduce the reconnect time, with or without the VPN software running.

The tests showed us the importance of antenna configuration in communicating with the robots. On the drop-off ad hoc nodes, we noticed a substantial improvement in range just by moving the node from the ground to on top of an upright cinder block, a height increase of only about 0.45 m. Replacing the stock antennas on the drop-off nodes with longer antennas with a higher gain (and more flexibility for practical reasons) could yield better performance. Similarly, the R-Gator has two diversity antennas positioned more than 1.8 m off the ground. As the tests showed, with communication payloads operating identical software, the range of the R-Gators was greatly increased over PackBot performance. This replicated the results obtained by the CI-CN when diversity antennas were used in their own ad hoc network tests before the nodes were delivered. The stock internal PackBot communications also use a two-antenna diversity configuration, which was disabled for these tests. It would be worthwhile to investigate the use of the existing PackBot antennas with our payload or modifying the payload to also use the diverse configuration.

5.2 Informal Robotic Field Test (Adelphi Laboratory Center)

This was an informal test performed quickly to determine if a recently constructed ad hoc communications payload for a PackBot was operational. It was performed at the ALC on 25 May 2006 on a dead-end road leading to the back gate of the post. The road is paved with a gentle downhill slope and a "dog-leg" to the right. There is heavy forest cover on either side of the road.

5.2.1 Objectives

Since we had some extra time following the initial operational check of the payload, we decided to also test the operation of the ad hoc network in a multi-hop configuration in a slightly different manner than our multi-hop test at Fort Dix. In addition, we wanted to attempt an NLOS test, and the inclusion of multiple hops through ad hoc drop-off nodes allowed us to test the network performance as the road made a near 90-degree right-hand turn and the robot moved out of the line of sight.

Here, we chose to place the drop-off nodes at about 75% of the maximum one-hop distance for each hop. That is, we planned to drive the PackBot until network failure and then placed the next ad hoc node at roughly 75% of that distance. This was repeated for each hop until we ran out of drop-off nodes and/or the network failed. Each hop was one of the following: OCU to robot, ad hoc node to ad hoc node, and ad hoc node to robot. For this test, the VPN was turned off for all ad hoc nodes.

5.2.2 Results

The network successfully routed control and video to the OCU at a modest frame rate of 7 frames per second and resolution of 320x240 through two drop-off nodes. The total distance traversed was 483 m. The hop from the second drop-off node to the robot was around the 90-degree bend in the road, creating an NLOS situation between the robot and the OCU.

5.2.3 Discussion

This was an informal test to ensure the payload was working. It is being included in this document solely for the sake of complete disclosure.

The network operated as anticipated. However, we noticed one issue involving network routing latency. When the robot reached the "end" of the network, we placed an ad hoc drop-off node at approximately 75% of that distance, as described. Leaving the robot where it failed, one would expect that the robot would regain connectivity following the power-up of the newly placed drop-off node. However, it tended to take 2 to 3 minutes for the network to discover that it could route through this new ad hoc node. Thus, there was a noticeable delay after the drop-off node was powered on before video and control of the robot were regained by the OCU. This is currently being investigated by CI-CN and will be re-evaluated further in the next formal round of testing.

5.3 Formal Robotic Field Test (Adelphi Laboratory Center)

Before to leaving for Fort Dix for the formal UGV evaluation, we wanted to do additional performance testing on the robotic control network in different configurations, as well as fully test the PackBot payloads with their new antennas, added per the results of a previous test (initial robotic field test)[13]. The tests were performed at ALC on 1 June 2006 in the parking lot next to and on the roads surrounding the Harry Diamond buildings, as well as in a wooded area between CISD's tents and the path on the western edge of the installation.

5.3.1 Objectives

The goal of these evaluations was to do more rigorous testing on the robot-OCU pair to determine how the ad hoc network responded to non-standard configurations that had not yet been evaluated. The first objective was to determine the distance over which the ad hoc communications system could acceptably operate a robotic asset using multiple hops through ad hoc drop-off nodes. Next, we determined the performance of the ad hoc network in NLOS applications using multiple ad hoc drop-off nodes. This included determining the feasibility and performance of the ad hoc network in a "mesh" configuration (i.e., blanketing a large area with multiple drop-off nodes). We also hoped to determine the performance of the ad hoc network over multiple hops when a robotic platform (PackBot, R-Gator) rather than an ad hoc drop-off node acted as an ad hoc relay node. Finally, we wanted to determine the performance of the ad hoc network in heavily wooded environments. These tests were performed with the VPN turned off because of configuration limitations.

Because this evaluation was in preparation for the formal UGV evaluation taking place at Fort Dix, we hoped to mimic some of the evaluations that the C4ISR OTM evaluators would be performing on our robots, such as target detection distance and target classification[14].

5.3.2 Results

In performing the NLOS test, we attempted to drive a PackBot all the way around the Harry Diamond building complex at ALC. Ad hoc drop-off nodes were placed on curbs at the four corners of the complex. When possible, they were placed on something that raised their heights by a small amount (less than 3 feet). The OCU was situated on a small cart on the sidewalk adjacent to the east side of the complex. The PackBot was driven in a counter-clockwise direction around the buildings. Connection was not established between all the drop-off nodes at the onset of the test. The PackBot was successfully driven down the front side of the building to the second closest drop-off node. However, that drop-off node could not make a connection with the next drop-off node. Our hope was that the PackBot would act as a relay between the two nodes as it moved between them. However, because of the elevation change between the two

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[13]Although the PackBot tested in the initial robotic field test had the new antenna, the remaining PackBot communications payloads still had a different, rigid antenna installed. This test confirmed operation of the antennas added to the remaining PackBots.

[14]Jennings, R., "UGV Evaluation" Mitre Corp.

nodes on the far side of the building, communications failed. The PackBot reached just over half way around the building complex. Attempts were made during the test to increase the height of the drop-off nodes suffering from lack of connectivity in hopes of creating a network connection. In certain cases, a link was created as a result of this but would only increase the controllable distance of the robot for a few feet before the link was broken again. Several changes were made in the ad hoc node software during the experiment in attempts to mitigate these issues. These included increasing the time tolerance in an effort to increase the distance at which the robot was able to be controlled and to decrease the beacon time. Neither of these changes resulted in substantial improvements in connectivity or performance.

For the mesh connectivity test, ad hoc drop-off nodes were placed at the four corners of the main parking lot adjacent to building 202 at ALC. The OCU was kept in the same location on the east side of the building. We used the CI-CN ad hoc connectivity visualization software to visualize connections and their strength between all ad hoc nodes. This diagnostic software indicated that all the ad hoc nodes had connections to every other ad hoc node immediately after all the devices were powered up. The robot was driven across the parking lot with no loss of connection or reduction in video quality.

Evaluating the robots in the wooded area proved to be pertinent to the environment the robots would be operating in at Fort Dix. We had not been able to communicate, using the old ad hoc communications systems, through a heavily wooded area approximately 150 m in extent. This test was to stand at a clearing on one side of the woods with the OCU and attempt to drive the PackBot through this 150-m woods with no ad hoc drop-off nodes. If the robot could not be controlled the whole distance, an ad hoc drop-off node would be placed part way.

While performing the test in a heavily wooded area, we drove the PackBot into a large downed tree branch which punctured the ad hoc payload. Upon the PackBot's encounter with the branch, the power to the payload was interrupted. Since we were unable to regain communications with the robot, testing was suspended for the day, since our only ad hoc payload had been damaged (the others were on site at Fort Dix). We learned that the branch had merely knocked loose one of the power wires in the payload, which suffered no significant internal damage.

Thus, not all of the objectives were achieved, for two reasons. First, the recently constructed ad hoc drop-off nodes requiring testing were not completed in time, mainly because of procurement delays. Secondly, the ad hoc payload on our test PackBot was rendered temporarily inoperable by the aforementioned tree branch while we were performing the wooded area testing.

5.3.3 Discussion

There are a number of issues that we believe to have contributed to the failure of the NLOS test. Most notably, the elevation changes around the building affected the performance of the network. Because the PackBot and the ad hoc drop-off nodes operate very low to the ground, many times there is no line of sight connection between nodes even over very small rises.

Although this does not often sever the link created, it can significantly decrease the signal strength, causing a drop in available video frame rate, which greatly affects the user's ability to drive a robot.

Through monitoring the network visualization software, we observed some "oscillation" between which nodes the robot would route through when in view of two nodes. The delay in packet forwarding as routes switched between nodes caused a noticeable lag in the video display in CollectControl, making it difficult to control the robot. We hypothesized that this was caused because the VPN was turned off. However, we were not able to verify that claim during this test.

The initial mesh connectivity test was inconclusive. In short, the network performed too well. We had hoped to see the robot moving across the parking lot and connecting to the closest node(s) as appropriate, but instead, we saw the robot connect to all the nodes at once. We clearly need to perform this test in a larger area or perhaps in more diverse terrain (wooded, hilly) to be able to observe varying behavior.

5.4   Preliminary UGV Evaluation (Fort Dix, New Jersey)

Because the C4ISR OTM program managers wrote their UGV evaluation, based on a less-capable UGV platform that was used in the experiment the previous year, they thought it advantageous for us show them some capabilities of the robotic systems and the ad hoc network before the formal UGV evaluation. We used this as an opportunity to perform more tests and to observe the behavior of the network in the field. The evaluation was performed on Tactical Range 9D at Fort Dix on 6 June 2006 under overcast conditions.

5.4.1 Objectives

The test we devised was to drive on the dirt trails in the heavily wooded area from a clearing. The robot was driven until control was lost, then an ad hoc drop-off node was emplaced, control regained, and the operator continued to drive the robot until the procedure stopped working. Given the environment, this allowed us to simultaneously evaluate the network performance in NLOS, wooded, hilly, and non-urban environments.

5.4.2 Results

We drove the PackBot down a canyon-like trail that sloped away from the OCU until we lost control. We then placed ad hoc drop-off nodes in line of sight from the OCU to the drop-off to the robot at the highest location we could using the terrain. The original plan was to use one or two drop-off nodes to get through the trail to a clearing where a target HWMMV was located, and take a picture of it in CollectControl. We accomplished that easily using only one drop-off node, so we continued adding nodes to the network and drove the PackBot farther away from the OCU. After adding a second node, we were able to drive it so far that it took us nearly 10 minutes to locate the robot, as when driving the operator was simply driving toward open, sandy areas, with no concern for where the robot was on the map. It is very easy to get

disorientated when tele-operating the robot in this manner. Although the robot appeared in its correct location on the mapping system, limitations in map resolution and the hilly, wooded terrain made it difficult to locate. After finding the robot, we were able to drive through 3 and 4 nodes before we decided to stop when control was becoming questionable. Control became more bursty with the video freezing and suddenly displaying all frames as control was routed through more network hops and the distance between nodes increased. No formal distances were measured in this evaluation, but they were comparable to those obtained in the first Fort Dix field test at the beginning of May.

5.4.3 Discussion

This evaluation was considered a success, as it demonstrated to the program managers that our robotic system was more than capable of providing a wide range of possible operating scenarios.

As seen in previous tests, there were times when the network was approaching its maximum working distance and connectivity temporarily dropped out, causing CollectControl to release control of the robot, even though it immediately had a strong frame rate following the glitch. As noted elsewhere, this behavior is the result of a conscience decision made for safety concerns.

We also observed that video from the PackBot was limited to frame rates of three to four frames per second at very close distances to the OCU (less than 3 m). This is the result of deliberate tuning of the ad hoc routers performed during this evaluation, allowing for greater control distance at the expense of throughput at short ranges. In most operating scenarios, this is not an issue.

5.5   UGV Evaluation (Fort Dix, New Jersey)

Researchers from HRED were present at the evaluation to gather human factors data on the human operator-PackBot system interaction. We anticipated an excellent outcome of this test since the PackBot was designed to operate in urban environments rather than the heavily wooded environments it had encountered thus far. The evaluation was performed at the Time Square military operations in urban terrain (MOUT) site at Fort Dix on 8 June 2006. This MOUT site consisted of a number of dirt streets lined with buildings made of large, metal shipping containers. The buildings contained various furnishings, such as tables, chairs, and mannequins representing civilians. Many buildings were two stories and had interior or exterior staircases. Also present at the site were numerous cars parked on the sides of the roads. One road continued past the MOUT site, as if heading to the suburbs and provided +0.25 mile of straight, flat road.

5.5.1 Objectives

The primary objective of the evaluation was to demonstrate the capabilities of our robotic system in an urban environment. This included how well the ad hoc network functioned in an environment full of reflective metal surfaces and obstructed views. Although unrelated to

network performance, we also hoped to show the urban environment capabilities of the PackBot, such as stair climbing and operation in the dark.

5.5.2 Results

The first test we ran was a straight line distance test. Although similar tests had been performed on uneven terrain, this test offered a very flat, straight stretch of dirt road on which to test. In addition to taking advantage of the road, we thought it would be interesting to see if the alley at the beginning of the road, through which the robot would pass, would challenge the network. Standing at the entrance to the MOUT site at the beginning of the dirt road, we were able to operate the PackBot and R-Gator as far as 386 m and 402 m, respectively. These distances were actually better than our initial straight line testing performed in June. Although we lost the ability to control the PackBot at that distance, the R-Gator still had a good connection but was at the end of the road.

The next test was evaluating the NLOS performance in the urban environment. The goal was to drive the robotic platforms all the way around the triangular city block at the MOUT site. We hypothesized that on the far side of the block, the significant amount of metal buildings would most likely severely affect the network. With the operator inside one of the metal buildings, the connection was lost and drop-off nodes were placed at the corners of the block. This allowed continued successful driving of the PackBot, with the OCU maintaining a reasonable frame rate and good control of the robot the rest of the way around the block. With the operator standing at the entrance to the MOUT site, the PackBot was able to be driven all the way around the block without the use of the drop-off nodes. The R-Gator was able to drive half way around the block during its test, going just out of sight around the corner. However, at that point, a mechanical failure on the R-Gator resulted in it having to be withdrawn from the test.

The final test required an operator to clear a two-story building from a concealed location in a building across that street. Of interest was whether a tele-operated robotic search could be completed with an acceptable level of thoroughness and in a timely manner. The operator sat in a chair away from windows on the ground level of one of the buildings along a road in the MOUT site. The robot was placed at the entrance to a different building across the street. Using only the OCU, the operator then attempted to clear the building, which involved checking all rooms on both levels for civilians (mannequins) and, if detected, taking imagery of the civilians. This would test the ad hoc communication network's ability to operate between two metal buildings in an urban environment and the effectiveness of using a UGV for this type of reconnaissance. The test was performed four times in buildings of various configurations. The system demonstrated good utility in this exercise, clearing a two-story building, including going up and down stairs in the dark, in 10 minutes. Overall, the operator was able to correctly identify 88% of the civilians in a building, with the PackBot having some trouble finding targets that were not easily apparent from its low vantage point. However, had the operator taken more time

in each room to maneuver the PackBot camera arm, the probability of detection may have improved.

Figure 8. PackBot operating at MOUT site.

5.5.3 Discussion

The main issue we expected to see in this evaluation was network degradation caused by buildings, since metal tends to reflect wireless signals in unpredictable ways, causing severe multi-path interference issues. However, these effects were largely unnoticed. In the straight line distance test, we observed much better distances than we did in an open field. This may have been attributable to the ground being flatter than at the initial test site, but the fact remains that the buildings did not contribute negatively to the performance of the network. Similarly, when attempting the building-clearing behavior, we expected the network to become questionable as soon as the robot entered its objective building. Again, however, the network performed well, with strong connectivity throughout the building. The only time anticipated network problems actually occurred was when we drove the robot around the block. We expected the connection to drop on the far side of the block, since there was a large amount of structure between the OCU and robot. As expected, the connection dropped when the operator was located indoors. However, the network regained its previous performance when the ad hoc drop-off nodes were placed in the intersections on the corners of the block and never lost a level of performance when the operator was outdoors. We had expected to see more interference

issues related to the large amount of sheet metal at the MOUT site but were encouraged when that did not occur.

5.6   C4ISR On-The-Move Experiment (Fort Dix, New Jersey)

All this testing and evaluation was in preparation for three weeks (10 July 2006 to 28 July 2006) of experimentation to be performed by trained United States National Guard Soldiers. Throughout the three-week period, varying sets of technology were combined and given to the Soldiers for use in mock operational scenarios. The goal was to determine how well the future technologies might improve the Soldier's SA, at dismounted and higher echelons.

The actual "experiment" was really a demonstration, since experimentation with the systems had already taken place. No changes were made in the network over the course of the three weeks, and it performed as we had anticipated. In fact, the biggest problem with the robotic control system had nothing to do with the technology itself but in getting the Soldiers to use the technology. There was some frustration among CISD folk regarding how and how much our equipment was used by the Soldiers in the field. CISD engineers provided adequate training before the experiment to familiarize the Soldiers with the capabilities and controls of the unmanned systems. However, this is indicative of a larger Army doctrine issue relating to the use of unmanned systems, not issues with the technology itself.

Two technology related issues did present themselves during the experiment. The first was an issue of communicating in very dense forest locations on a few occasions. It was reported to us that when a Soldier was attempting to drive a PackBot from a prone position in deep wooded cover, the operational range was reduced to approximately 9 m. Although there are possible physical limitations of the system at play here, with the antennas on the OCU and PackBot being very close to the ground and severely obstructed paths limiting connectivity, the result was surprising. This poor level of network performance had not been exhibited during any of the previous tests. Because of experimental design constraints, we were not able to observe or troubleshoot this issue in the field during the exercise as it occurred.

The second issue was specific to the R-Gator. CISD added a high-powered camera to the R-Gator platform, a DI-5000 made by Digital Infrared Imaging, Inc. When the DI-5000 was pointed at a visually complex scene, such as a very densely wooded environment at close range, the packets that the Motion-JPEG video compression scheme created were very large. It was observed that when the camera was pointed toward such scenes, the ad hoc network did not forward the packets at a resolution of 320x240, the default CollectControl resolution. This was confirmed when a lower resolution (160x120) was specified; lower quality video containing smaller packets streamed over the ad hoc network. As a workaround, the Motion-JPEG compression level for the DI-5000 was increased. This resulted in smaller video packets that did not cause problems on the ad hoc network; however, the higher compression level substantially decreased the quality of the image. Both of these issues will be further examined at ALC.

6. Conclusion and Future Work

As a whole, ARL's involvement in the C4ISR OTM experiment was a success. The MANET and robotic platforms performed admirably with minimal issues throughout the summer, often enduring 100 °F and high humidity. However, as noted, there are three issues that need to be further investigated (bursty video, the large packet issue, and reduced network performance in heavily wooded areas). The likely candidates in the bursty video issue are the ad hoc routing protocol and CollectControl. The ad hoc software will be examined to determine if it is queuing the video frames, and CollectControl will be studied to possibly include an algorithm to discard old video frames so they are not displayed. The solution to this issue could impact the resolution of the other two. There is a test plan in place for further investigation of these issues, and it will be conducted as time and manpower allow.

Work will continue on the operation and evaluation of this network in true ad hoc fashion, without the VPN activated. Although its application in this experiment (as an end-to-end network with the ability to use any drop-off node) had its advantages, the true benefit of an ad hoc network lies in its ability to connect a large group of mobile nodes. As such, provided that higher level network architecture does not prevent it, the network will be implemented as a true MANET.

After watching Soldiers use the ad hoc drop-off nodes in a field environment, we observed that they often had difficulty emplacing the nodes in locations that would improve network connection and/or performance. It could be beneficial to include a utility for visualizing network strength and connectivity on the OCU, aiding the Soldiers in intelligently placing the nodes. Such a piece of software exists in CI-CN, but it does not easily lend itself to integration into an OCU-user interface. Further investigation into how best represent this information to the user will occur in the future.

Ongoing research into quality of service and intrusion detection for MANETs is being performed at ARL. It is hoped that these research areas will lead to more secure and robust ad hoc networks and could be implemented on the MANET discussed in this document.

Finally, as the robotic platforms that are controlled in an ad hoc network become smaller and more constrained, the packaging for the COTS wireless routers running the ad hoc software will need to be examined. Presently, the COTS pieces were used "as is," being strapped to the back of the OCU or inserted into large payload containers on the mobile platform. As the platforms shrink, so does their ability to carry large, modular payloads. A highly integrated approach to developing the communications hardware may need to be investigated.

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